A Statistical Model for UWB Non-line-of-sight Indoor Environment

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Abstract

A new double-cluster statistical model for non-line-of-sight (NLOS) environment is proposed which is based on analysis of the experimental data. The model itself and the parameters estimating of the corresponding model are simplified. By defining the polarity of a particular model parameter, the model has the flexibility to deal with the "soft NLOS" and the "hard NLOS" environment. Therefore, the channel impulse responses (CIR) generated by the proposed mode "resemble" the measured channel impulse responses better than SV/ IEEE 802.15.3a model in terms of the cumulative distribution functions (CDFs) of the small-scale statistics, instead of just the average values.

1. INTRODUCTION

The development of short-rang and high-speed transmission systems is going to play a significant role in the area of wireless communications [1]-[4]. This has motivated the exploration of the ultra-wide-band (UWB) transmission system. The Federal Communication Commissions (FCC) recognized the significance of UWB technology in 1998. On February 14, 2002, the FCC commissioners unanimously approved limited uses of UWB, which has greatly motivated the development of UWB technology.

Generally, UWB communications is based on the transmission of very short pulses with relatively low radio energy. The indoor propagation channel appears differently to UWB wireless systems than it dose to narrowband (NB) sine wave systems for UWB impulses are short and generally don't overlap like multipath sine waves. Furthermore, for non-line-of-sight propagation, UWB radio signal arriving at the receiving antenna consists of multipath components, each of which is the result of the heavy interaction of the transmission impulse with the surrounding objects in an indoor environment. Therefore, the correct multipath models of UWB pulse transmission in non-line-of-sight environment play a fundamental role in the design and implementation of the UWB systems.

Several ways exist to build a model of the mobile radio propagation channel. One major way is to use stochastic methods, which describe the random behavior of the UWB wireless channel at any time and for different propagation environments using a statistical approach. The IEEE 802.15.3a standards body has established a modification of the Saleh-Valenzuela (SV) model [5] as the accepted standard NLOS channel model for UWB investigations. The SV/IEEE 802.15.3a model [5]-[7] is a well-defined statistical model that is straightforward to implement, unfortunately, it also has drawback: channel impulse responses generated by this model display a large amount of visible random arriving clustering, which is not "resemble" the measured channel impulse responses[8]. This makes one cannot easily obtain accurate estimates the cluster arrival rate (one of the 6 key parameters of the SV/IEEE 802.15.3a model) from the measurement data (the work can only be done manually until now). It also makes it hard to match the exact distribute of the small scale statistics, although, the average values of them are matched.

The measurements made by Moe Win in UltRa Lab (1995) [9]-[11] show that the measured channel impulse responses do not display significant clustering as opposed to the SV/IEEE 802.15.3a model, even if the small scale statistics of the mean excess delay, RMS delay spread and the number of significant multipaths of the two are matched (in average values sense). The measurements also show that the "soft NLOS" and the "hard NLOS" environment may have totally different channel impulse responses at all.

In this work, a new NLOS statistical model with the arrival of a fixed number of two clusters is presented. The model itself and the estimation of the corresponding model parameters are simplified in comparison with SV/ IEEE 802.15.3a model. Furthermore, by defining the polarity of ray decay factor of the two clusters, the model has the flexibility to deal with the "soft NLOS" and the "hard NLOS" environment. Simulation indicates that the CIRs generated using the proposed mode "resemble" the measured channel impulse responses better than SV/ IEEE 802.15.3a model in terms of the CDFs of the small-scale statistics, which means the proposed double-cluster statistical model is more accurate in modeling our set of small-scale NLOS environment than the well-known SV/IEEE 802.15.3a model.

In Section 2, the UWB propagation experiments and relevant analysis are described. The definition of proposed statistical model is given in Section 3. The simulation results generated based on our proposed model are discussed and compared with the experimental data in Section 4. Finally, Section 5 gives the conclusions.

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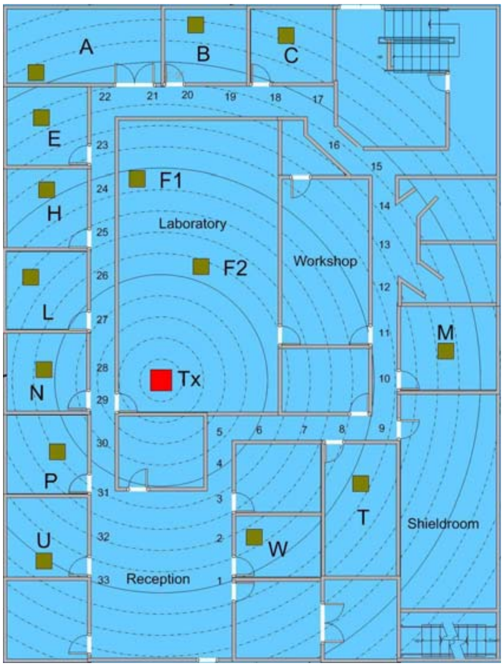

Fig. 1: A diagram of the modern office building where the propagation measurement experiment was performed. The concentric circles are centered on the transmit antenna and are spaced at 1-m intervals. Form [13].

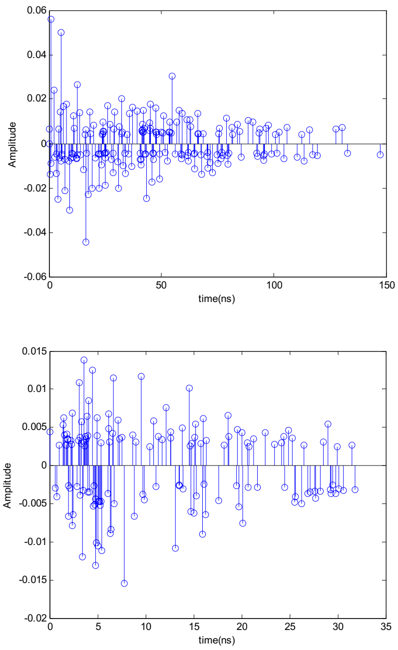

Fig. 2: Typical channel impulse responses for "soft NLOS" and "hard NLOS" environment (The upper trace is in office L and the lower trace is in office T. The distances are 8 and 26.6m away from the transmitter, respectively)

2. Measurements and Analysis Results

A growing number of measurement campaigns have been carried out to characterize the UWB channel. These works include time domain, i.e. direct pulse, measurements and frequency domain measurements using vector network analyzers [12]. In this paper, we present a statistical analysis of the data collected by Moe Win (in UltRa Lab of University of Southern California) in 1995. The experimental data can be accessed freely via the World Wide Web from [13].

Win's UWB propagation experiment was performed in a modern laboratory/office building having the floor plan shown in Fig. 1. The technique employed in this measurement campaign is to probe the channel periodically with nanosecond pulses and to record its response using a digital sampling oscilloscope. The details of the measurements set-up, and data format can be found in [10], [11].

CLEAN [14], [15] algorithm was used to extract the CIR from Win's measurements of the received waveforms. The template for the CLEAN algorithm was also obtained from Win's measurement [13] which was made with one-meter separation between transmit and receive antennas and used the first few nanoseconds of the obvious response function. CLEAN algorithm searched the experimental received waveforms iteratively to find the maximum correlation of the template [14] and gave the channel impulse responses of the 12 NLOS environments. By setting the energy threshold (the energy difference between the received waveform and the recovery waveform obtained by convolution of corresponding CIR and template) to be 30%, only the CIRs measured in offices H, L, P, N, M, U, and T are within this scope.

It showed that the 7 NLOS environments could be divided into two categories: "soft NLOS" (including office H, L, P, N, and M) and "hard NLOS" (including office U, and T). For "soft NLOS" environment, the excess delay is always zero for the multipath component that has the maximum path gain. However, for "hard NLOS" case, it is nonzero. A typical channel impulse response for both cases is shown in Fig. 2.

In any case, no more than two clusters can be distinguished from channel impulse responses. Therefore, it is reasonable and necessary to make the new statistical model have fewer clusters than SV/ IEEE 802.15.3a model, at the same time have the enough degrees of freedom to deal with "soft NLOS" and the "hard NLOS" environment.

3. The Proposed Statistical Model

The SV/ IEEE 802.15.3a model is based on the generation of multiple exponentially decaying clusters. However, as shown in Section 2, Win's measurement data indicates that very few clusters may exist in channel impulse responses for both cases. In this Section, a double-cluster statistical model is proposed as a modification of SV/ IEEE 802.15.3a model. The model assumes that rays generally arrive in two clusters, one delayed by a random time interval relative to the other. Moreover, in order to maintain continuity in the decay of energy in the overall CIR, the first cluster is weighted higher than the second cluster by a factor a^2. The subsequent rays within each cluster are modeled as a constant-rate Poisson arrival-time process with mutually independent lognormal distribution multipath gain and exponential decaying average power.

Therefore, the multipath model is consisting of the following discrete time impulse response:

$$h_i(t)=\sum_{k=0}^{M}\alpha_{k,1}^i\delta(t-T_1^i-\tau_{k,1}^i)+\sum_{k=0}^{N}\alpha_{k,2}^i\delta(t-T_2^i-\tau_{k,2}^i)$$

where $\{\alpha_{k,m}^i, m=1,2\}$ is multipath gain coefficient of cluster m, $\{T_m^i, m=1,2\}$ is the arrival time of clusters m, i.e., the arrival time of the first ray of cluster m. Within each cluster, $\{\tau_{k,m}^i, m=1,2\}$ is the arrival time of the k^{th} multipath component measured from the beginning of the cluster, M is the path number of the first cluster, N is path number of the second cluster.

A. Distribution of Ray Arrival Time

Let the arrival time of the first cluster be reference time, then $T_1^i=0$. Let the time delay between two clusters be denoted by T_N, thus we have $T_2^i-T_1^i=T_2^i=T_N$. Hence, $\tau_{0,m}=0(m=1,2)$.

Rays within each cluster are modeled as a Poisson arrival process. Furthermore, let the arrival rate of path within each cluster has the same fixed value λ. Thus, the distribution of the ray arrival time within each cluster is given by

$$P(\tau_{k,m}\mid\tau_{k-1,m})=\lambda\exp[-\lambda(\tau_{k,m}-\tau_{k-1,m})], m=1,2$$

B. Distribution of Channel Coefficients

Let the gain of the k^{th} ray of the m^{th} cluster be denoted by $\alpha_{k,m}$, then the channel coefficients are defined as follows:

$$\alpha_{k,m}=p_{k,m}\beta_{k,m}, m=1,2$$

where $p_{k,m}$ is used to account for the random pulse inversion that can occur due to reflections and is equally likely to take on the values of +/-1. Lognormal fading term $\beta_{k,m}$ is given by

$$20\log10\beta_{k,m}\propto Normal(\mu_{k,m},\sigma^2), m=1,2$$

C. Ray Power Decay

The average power gain of the first cluster is weighted higher than the second cluster by a factor a^2.

$$E[|\beta_{0,2}|^2]=a^2E[|\beta_{0,1}|^2], 0<a<1$$

The average power gain of the rays within each cluster decays exponentially with ray delays. The ray decay factor is γ_m, and it usually assumes $\gamma_1<\gamma_2$.

$$E[|\beta_{0,m}|^2]=\Omega_{0,m}e^{-\tau_{k,m}/\gamma_m}, m=1,2$$

where $\Omega_{0,m}$ is the mean power of the first path of the first cluster. $\mu_{k,m}$ is given by

$$\mu_{k,m}=\frac{10\ln(\Omega_{0,m})-10\tau_{k,m}/\gamma_m}{\ln(10)}-\frac{\sigma^2\ln(10)}{20}, m=1,2$$

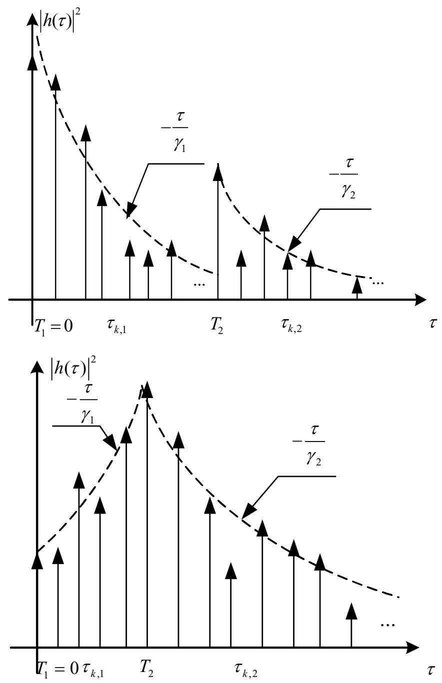

Fig. 3: The average power of two kinds of NLOS environments generated by double-cluster statistical model. The upper trace is for "soft NLOS" case and the lower trace is for "hard NLOS" case.

D. Definition of model parameters

By defining the polarity of ray decay factor for each cluster, the double-cluster statistical model can deal with the two kinds of NLOS environments mentioned in Section 2. Let $\gamma_1>0$ and $\gamma_2>0$, the excess delay is zero for the multipath that has maximum path gain because the average power gain of the first cluster is greater than that of the second one, and it decays monotonously for both clusters. Thus, $\gamma_1>0$ and $\gamma_2>0$ are suitable for modeling "soft NLOS" environment. Let $\gamma_1<0$, then the average power gain of the first cluster monotonously increases, if still let $\gamma_2>0$, the excess delay will be nonzero for the multipath that has maximum path gain. Then, $\gamma_1<0$ and $\gamma_2>0$ are suitable for modeling "hard NLOS" environment. Therefore, the model has the flexibility to deal with the two kinds of NLOS environments by defining the polarity of single model parameters. A sketch that clarifies our model up to this point is given in Fig. 3.

TABLE 1: PARAMETERS OF DOUBLE-CLUSTER STATISTICAL MODEL

Ray Arrival Rate	λ
Average Power Gain Factor	a^2
Time Delay between Two Clusters	T_N
Decay Factor of the First Cluster	γ_1
Decay Factor of the Second Cluster	γ_2
Standard Deviation of Lognormal Fading Term (dB)	σ

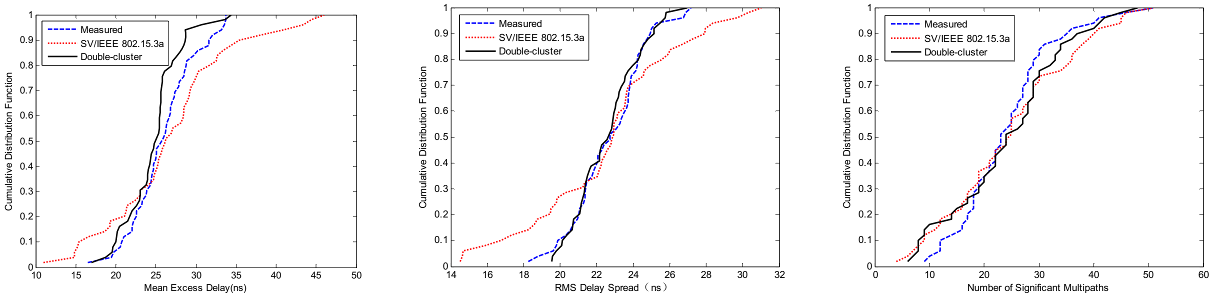

Fig. 4: CDFs of the three channel characteristics in office L

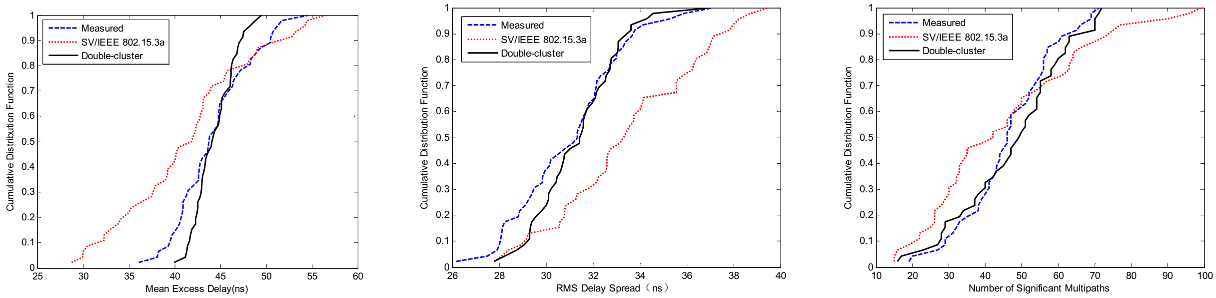

Fig. 5: CDFs of the three channel characteristics in office T

As shown above, there are six key parameters that define the model (listed in Table I.). Apparently, the double-cluster statistical model is easier to use for the parameters that must use Brute Force (BF) [6] search to fit the model to measurement data are reduced from seven (the SV/IEEE 802.15.3a model) to six. In addition, and perhaps more importantly, the channel impulse responses generated using this model have a fixed number of two clusters, thus making the cluster arrival rate be a constant, which avoids the tedious and inaccurate work of distinguishing clusters from the measured channel impulse responses.

4. EMPIRICAL ANALYSIS OF DOUBLE-CLUSTER MODEL

Previous approaches in UWB channel modeling compared only the average values of the three key channel characteristics like the mean excess delay, RMS delay spread and the number of significant multipaths components[16],[17]. It can be shown that it is possible to match the average values of these parameters without matching the exact statistics of these characteristics. Our goal in this section therefore is to find appropriate parameters of the two models (the double-cluster statistical model and the SV/IEEE 802.15.3a model) that generate impulse responses with the closest CDFs of the characteristics mentioned above to the corresponding CDFs of our set of measured channel impulse responses, and then evaluate the performance of the two models.

For the double-cluster statistical model, BF search was performed to find appropriate parameters that generate impulse responses with the closest CDFs of the characteristics, i.e. the mean excess delay, RMS delay spread and the number of significant multipaths that cross a 10 dB threshold, to the corresponding CDFs of the measured channel impulse responses. For the SV/IEEE 802.15.3a model, the same proce--dure was performed and appropriate parameters were also computed from the same set of measured channel impulse responses. Fig. 4 and Fig.5 compare the performance of the SV/IEEE 802.15.3a model with the double-cluster statistical model in terms of CDFs of the three key channel characteristics.

It shows that for win’s specific measurements, the proposed double-cluster statistical model fits the data better than SV/IEEE 802.15.3a model in the sense of the three channel characteristics’ CDF, which means the proposed model generate impulse responses "resemble" the measured channel impulse responses better than SV/IEEE 802.15.3a model. It can be explained instinctively that with the flexibility to shaping the CIRs, the double-cluster statistical model is more suitable for modeling the NLOS environments with great difference.

It is appropriate to mention at this point that win’s measurements have a time resolution of 2ns, which is limited by their measurement system. An alternative high resolution measurement setup may exhibit a large number of weak rays and clusters. However, we believe that the double-cluster statistical model is much simpler to work with in analysis and simulation than the well-known SV/IEEE 802.15.3a model, and is quite adequate for modelling our set of measured channel impulse responses.

5. CONCLUSIONS

Based on the analysis UWB experimental data, a new double-cluster UWB NLOS small-scale statistical model is therefore proposed. The model matches what have been found in our set of indoor NLOS UWB channel measurements and simplifies the input parameters acquiring procedure. The proposed model also provides enough degrees of freedom to match the "soft NLOS" and "hard NLOS" channel characteristics separately. When considering CDFs of the statistics such as the mean excess delay, RMS delay spread and the number of significant multipaths, the double-cluster statistical model outperforms SV/IEEE 802.15.3a model, which means the channel impulse responses generated using the proposed model resemble the measurement data better. Therefore, the proposed double-cluster model is more suitable and accurate in modeling our set of small-scale NLOS environment than the well-known SV/IEEE 802.15.3a model.

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